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Estimation of airline benefits from avionics upgrade under preferential merge re-sequence scheduling

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Modernization of the airline fleet avionics is essential to fully enable future technologies and procedures for increasing national airspace system capacity. However in the current national airspace system, system-wide benefits gained by avionics upgrade are not fully returned to aircraft/airlines that upgrade, resulting in a slow fleet modernization rate. Preferential merging is a best-equipped-best-served concept designed to incentivize avionics upgrade among airlines by allowing aircraft with new avionics (high-equipped) to be re-sequenced ahead of aircraft without the upgrades (low-equipped) at en-route merge waypoints. The goal of this study is to investigate the potential benefits gained by airlines under a high or low-equipped fleet scenario if preferential merging is implemented, using historical data for arrival flights into Phoenix Sky Harbor International Airport.

I. Introduction

MODERNIZATION of the airline fleet avionics is one of the essential factors to fully enable Next Generation Air Transportation System (NextGen) technologies and procedures for increasing National Airspace System (NAS) capacity. For example, onboard Automatic Dependent Surveillance-Broadcast (ADS-B) Out units provide significantly higher surveillance and control precision than is possible with conventional radars. With increased aircraft tracking precision, the minimum separation constraints between flights can be lowered, allowing air traffic controllers (ATC) to fit more aircraft in the airspace. ADS-B-In provides even more capacity to the NAS by allowing equipped aircraft to hear position reports from other nearby aircraft without going through ATC, further lowering the minimum separation constraints.[1] However, the cost to upgrade avionics on commercial aircraft is extremely high. For example, the Federal Aviation Administration (FAA) Advisory and Rulemaking Committee (ARC) estimated that for ADS-B-In equipage, depending on the aircraft type airlines will need to spend between \$130,000 – \$290,000 to forward-fit a single aircraft; \$270,000 – \$425,000 to retrofit in-production aircraft; and \$490,000 – \$700,000 to retrofit out-of-production aircraft.[17] This is a significant investment especially for the legacy

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airlines that operate a large fleet of older aircraft. The FAA mandated that all aircraft equip with ADS-B-Out by 2020.[2] However, despite the mandate, avionics upgrade rate has been slow and airlines have requested additional incentives to help bear the cost of equipping.[3]

Accelerating the airline fleet avionics upgrade rate will hasten the delivery of NextGen benefits. Several studies have already investigated ADS-B benefits and facilitation strategies. Many of these studies quantify ADS-B benefits from an air traffic management (ATM) perspective under current procedures,[4-7] or focus on the qualitative assessment of ADS-B benefits across various NAS stakeholder perspectives (e.g. passengers, airlines, airports, ATC, military, etc.).[8-11] Of these, only a handful of studies consider airline-specific benefits, operational incentives or utilize the nature of airline competition to increase ADS-B equipage motivation.[12-13]

Preferential Merging (PM) is a best-equipped-best-served, operational incentive concept designed to facilitate the avionics transition process by taking advantage of the airline industry's competitive nature. PM is a modification to air traffic schedulers like the Traffic Management Advisor (TMA)[14] that would reward aircraft with modern avionics such as ADS-B (high-equipped) by re-sequencing its arrival schedule at merge waypoints ahead of aircraft without the modern avionics (low-equipped), whenever possible. Delay risks, airtime and associated operating cost are "transferred" from high- to low-equipped flights, at the expense of avionics cost and extra fuel possibly required to execute the re-sequencing maneuvers. In the future, high-equipped flights will also be able to take more efficient routes such as required navigation performance (RNP) due to the higher surveillance precision.

The main objective of research presented in this paper is to investigate PM impact on en-route operations and corresponding cost/benefits on individual airlines, if they choose to upgrade their fleet avionics. Historical data of arrival flights to Phoenix Sky Harbor International Airport (PHX) on April 19th, 2012 in the Albuquerque en route Center airspace (ZAB) is considered for initial testing of the PM concept, using a queue-based, first-come-first-served air traffic scheduler. PHX was chosen for initial PM evaluation so that the analysis results can be in line with other research under the Air Traffic Management Technology Demonstration-1 (ATD-1) effort at NASA Ames, which has also investigated PHX air traffic operations in its testing. A companion paper[15] describes this scheduler in further detail. Research presented in this paper will also describe facilities in the NAS that are most likely to have high PM yield, based on the unique fleet allocation patterns of airlines investigated. In the future, PM can be expanded to provide incentives to aircraft not only based on avionics equipage but also other airline investments that benefit the NAS as a whole, such as increased utilization of greener aircraft with lower emissions and noise.

The remainder of this paper is organized as follows. Section II further discusses some of the reasons for low fleet avionics upgrade rate. Section III provides the technical approach taken to quantify potential airline benefits through PM. A description of the simulation tools is provided and data utilized for this study are also listed. Benefits analyses focused on PHX arrival flights across multiple airlines is shown in Section IV. An assessment of other airports with high PM yield potential for one of the airlines investigated is also included. Conclusions and future work based on the presented research are discussed in Section V.

II. Background: Lack of airline motivation for avionics upgrade

Reduced aircraft separation requirements attained through ADS-B benefit the airlines by increasing airspace capacity and reducing associated delays.[16] However, while the fleet is under a transition phase to upgraded avionics, a mixed equipage environment exists in which potential benefits are not properly directed to the aircraft/airline that first invests in the equipment. Figure 1 illustrates this phenomenon. Arrival sequence A is the baseline case, where the high-equipped aircraft avionics capability is disabled and all aircraft have equal separation requirements. In arrival sequence B, the high-equipped aircraft avionics are enabled and its separation requirements are reduced. In sequence B, low-equipped aircraft are receiving the benefits of airspace capacity increase without investing on avionics upgrade, becoming "free-riders."

The combination of high cost and unclear equipage benefits over non-equipping competitors is currently discouraging airlines to voluntarily invest in avionics upgrade, delaying the delivery of NextGen benefits. PM aims to redirect equipage benefits back to airlines that actually invest in avionics rather than the "free-riders." Figure 2 illustrates the PM concept, which is not designed to achieve any airspace capacity optimality by utilizing modern avionics capabilities. Rather, it is simply a motivation strategy to accelerate the avionics transition process by providing opportunities for airlines to gain an operational advantage over their competitors by upgrading their fleet avionics sooner. While PM benefits alone are most likely not capable of paying off the entire equipage cost, this concept will add on to other existing benefits (such as airspace capacity increase and reduction of associated delays) and further increase airline motivation for a shorter fleet transition period.

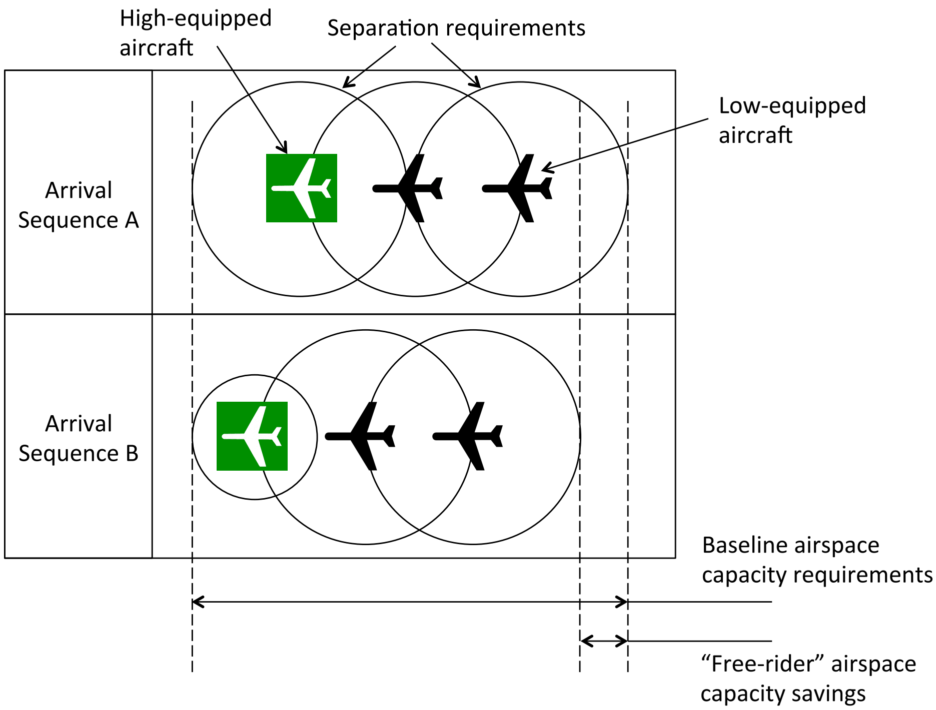

Figure 1. Airspace capacity savings under a mixed equipment scenario.

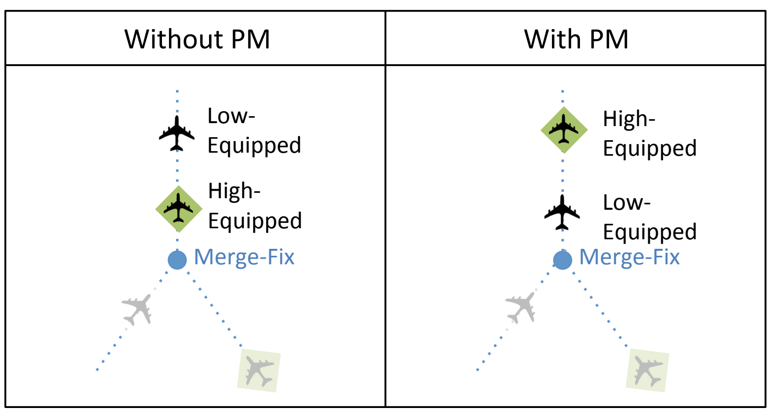

Figure 2. Illustration of PM impact on aircraft sequence.

III. Technical Approach

PM benefits are investigated in terms of a detailed, airport specific analysis and search for other airports with high potential in extending PM impact. The airport specific PM analysis quantifies the investment collection rates for airlines under various PM scenarios for PHX arrival flights merging at waypoints within the ZAB airspace. The airport search effort identifies airports across the NAS by their PM yield extension potential using PHX/ZAB as an anchor point, based on historical airline fleet utilization patterns, market share, and traffic conditions. A single nationwide carrier was selected for analysis in the airport search because PM yield can differ significantly by airline due to their unique fleet composition and operations across the NAS. Both the airport specific PM analysis and airport search assume an extreme scenario in which the focus airline fleet is 100% and its competitors are 0% high-equipped. Such an extreme scenario is unrealistic, but a useful assumption to simplify and reduce the analyses required to quantify PM benefits. Research reported in this paper mainly focuses on the financial analysis of the airport specific approach on PHX. Details on operational aspects of the PHX specific analysis is further described in the companion paper.[15]

Two simulation tools are mainly used for the airport specific PM study. First is the Airspace Concept Evaluation System (ACES),[18] which generates the baseline, unimpeded aircraft trajectories using historical flight data extracted from Airline Situation Display to Industry (ASDI) data. Second is the Preferential Merge Re-sequencing Scheduler (PMRS) which imports the ACES trajectories and creates a new set of trajectories with re-sequencing achieved via speed control, constrained by maximum cruise speed of individual aircraft type. A summary description of these tools are provided in Section IIIA and B. A fuel estimation procedure using the Base of Aircraft Data (BADA)[19] developed at NASA Ames then takes in the baseline and PM trajectories to calculate the difference in aircraft fuel burn and flight time. The ADS-B-In cost is divided by the change in direct operating cost (resulting from the difference in fuel burn and flight time between the baseline and PM trajectories) to calculate the PM investment cost collection time for PHX inbound aircraft. A flowchart that summarizes the overall approach for the airport specific analysis is shown in Figure 3.

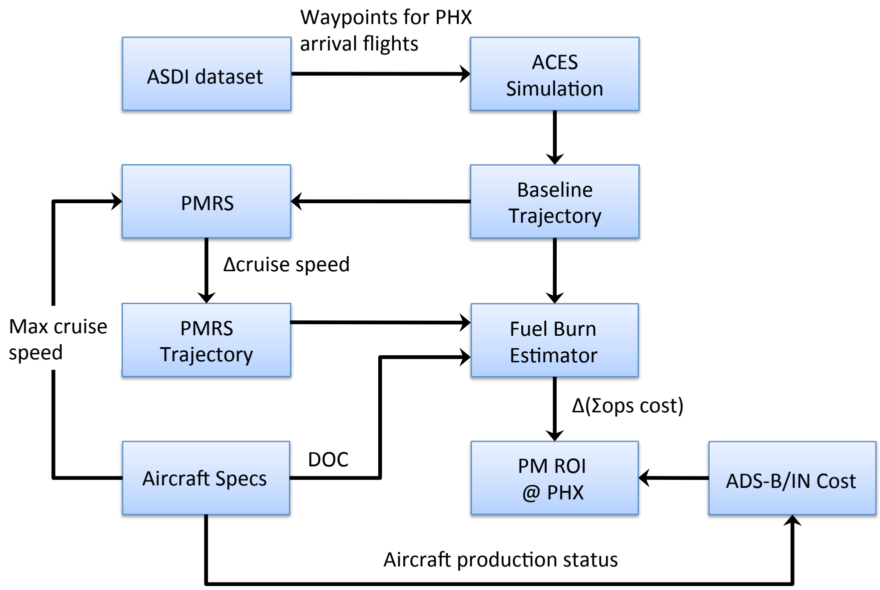

Figure 3. PM analysis flowchart.

Avionics cost was assigned to each aircraft type based on its production status, and the direct operating cost for each aircraft type was calculated using the DOC+I (Direct Operating Cost plus Interest) model developed by Liebeck[20] and Ross[21]. The DOC+I model uses aircraft specs such as thrust and maximum takeoff weight to estimate aircraft DOC, composed of flight & cabin crew cost, as well as airframe and engine maintenance cost. Interest, landing fee, navigation fee, depreciation, and insurance is included in the DOC+I model but was not considered for this research. Fuel cost was calculated separately by the fuel estimation procedure mentioned previously. Table 1 displays a sample set of the aircraft specification data collected from the manufacturers and the resulting hourly DOC from the DOC+I model.

Table 1. Sample DOC+I results for selected aircraft.

Aircraft	Max Takeoff Weight (lbs)	Operating Empty Weight (lbs)	Number of Engines	Engine Thrust (lbf)	Production Status	Est. ADS-B-IN Cost	Hourly DOC
A319	166,000	90,000	2	24,500	In Production	$270,000	$1,787
A320	170,000	94,000	2	27,000	In Production	$270,000	$1,805
B735	144,250	71,585	2	21,750	Out of Production	$490,000	$1,704
B737	154,500	84,468	2	26,300	In Production	$270,000	$1,758
CRJ2	53,000	30,900	2	9,220	Out of Production	$490,000	$1,470
CRJ7	75,000	43,500	2	13,790	In Production	$270,000	$1,537
E190	120,000	61,900	2	20,000	In Production	$270,000	$1,647

A. Airspace Concept Evaluation System (ACES)

The Airspace Concept Evaluation System (ACES) is a fast-time air traffic simulation tool developed at NASA Ames Research Center. Air traffic data are modeled in ACES by simulating trajectories according to aircraft models from BADA and historical flight path data obtained from ASDI. Current or future air traffic management technologies and concepts are implemented in ACES using an agent-based modeling framework that is capable of simulating the interaction of all of the key components of the NAS for a comprehensive gate-to-gate simulation. The simulated output data provide metrics that allow for a full assessment of the impacts of proposed concepts on the NAS.

In this study, ACES is utilized to simulate air traffic without ATC influence on the arrival sequence for PHX inbound flights. This was accomplished by configuring the simulation without airspace/airport capacity constraints and Traffic Flow Management (TFM) initiatives, allowing aircraft to fly at cruise speed across the entire recorded flight path from ASDI. The resulting unimpeded trajectories are then used to determine which merge waypoints are crossed by each flight and the corresponding crossing times. The simulated waypoint crossing data was verified and validated against historical data for accuracy.

B. Preferential Merge Re-sequence Scheduler (PMRS)

The Preferential Merge Re-sequencing Scheduler (PMRS) is a queue-based scheduler that creates merge waypoint crossing time schedules based on a nominal trajectory and aircraft avionics equipment status. For each merge waypoint, the scheduler first sequences the flights by their waypoint crossing times in the unimpeded ACES trajectories. The scheduler attempts to re-sequence any flights designated as high-equipped ahead of any low-equipped flights within a passing window. A passing window is defined as the amount of time that can be added or subtracted to the nominal cross-times by adjusting en-route cruise speed between the top-of-climb and top-of-descent points. An aircraft's increase in speed is limited to the max cruise speed derived from the manufacturer's specifications and its reduction in speed is limited to 10% of the nominal cruise speed from the unconstrained ACES simulation. The 10% cruise speed reduction is extracted from the commonly expected range of speed reduction for research related to Flight Deck Interval Management (FIM) and Controller Managed Spacing (CMS).[22] The passing window is also constrained by minimum wake-vortex separation requirements between flights and airport arrival constraints, which was fixed to 70 aircraft per hour based on Aviation System Performance Metric (ASPM) data. Note that PMRS is only a scheduler that manipulates aircraft arrival times to the merge fixes, and does not implement any altitude or path change maneuvers to comply with the re-sequenced schedule. Currently all aircraft are fixed to the paths extracted from ASDI, and only the cruise speed is modified to estimate the change in fuel consumption. Integrating the PMRS with a trajectory trial planner to implement altitude or path change maneuvers for a more complete PM cost and benefit analyses, is a topic of future work.

Speed changes can be executed in the order of speeding up high-equipped flights and then slowing down the low-equipped flights if necessary, or by slowing down the low-equipped first and then speeding up the high-equipped if necessary. PMRS can also be configured to only allow passing between merging flight paths, or between any paths. The two configuration options produce very different end results, and all four possible configurations, listed and labeled in Table 2 are examined in this study.

Table 2. PM Scheduler configurations examined.

PMRS Configuration	Passing allowed between:	Speed change command order
PMRS 1	merging paths only	1) Low-equipped slow down 2) High-equipped speed up
PMRS 2	merging paths only	1) High-equipped speed up 2) Low-equipped slow down
PMRS 3	any paths	1) Low-equipped slow down 2) High-equipped speed up
PMRS 4	any paths	1) High-equipped speed up 2) Low-equipped slow down

For passing between merging paths, a set of flight paths are considered to be merging if either of the following conditions apply.

1) average heading angle difference between the paths 15 minutes prior to the merge waypoint is larger than 7 degrees
2) average distance between the paths 15 minutes prior to the merge waypoint is greater than 5 nautical miles.

Aircraft on the same paths can be re-sequenced only in PMRS 3 and 4. However, in either passing options, the aircraft in the pair must be operated by different airlines for any re-sequencing considerations. No re-sequencing is done between flights operated by the same airline, although this feature can be enabled in a future Collaborative Decision Making (CDM) study with airlines. Additional details on the PMRS software are described in the companion paper.[15]

IV. Results and Discussion

PM benefits are investigated for four airlines; two nationwide and two regional. The PHX case study discussed here considers flights bound to PHX between 4:00 AM and 11:00 PM MST on April 19th, 2012 over a total of eight merge waypoints inside ZAB. Flight paths for one of the nationwide airlines are displayed in Figure 4. At PHX, more than 600 flights operated by 25+ different airlines arrive daily; approximately 80% of those flights are operated by the four airlines, denoted as A, B, C and D. Airlines A and B are nationwide carriers, whereas C and D are regional. Figure 5 breaks down the volume of air traffic that passes through each merge waypoint from Figure 4 by its operating airline. Some flights in Figure 5 are counted for multiple merge waypoints depending on the arrival procedure. Using this air traffic data, Section IVA investigates the PM operational gain and associated cost. Findings in Section IVA are carried over to Section IVB where the operational gains/cost are coupled with the ADS-B-In cost and aircraft DOC to evaluate the overall PM investment cost collection times. The expected fleet ADS-B-In equipage payoff period and achievement rate is also estimated. Section IVC introduces an approach to identify other airports estimated to have high PM yield-extension based off of PHX for airline B.

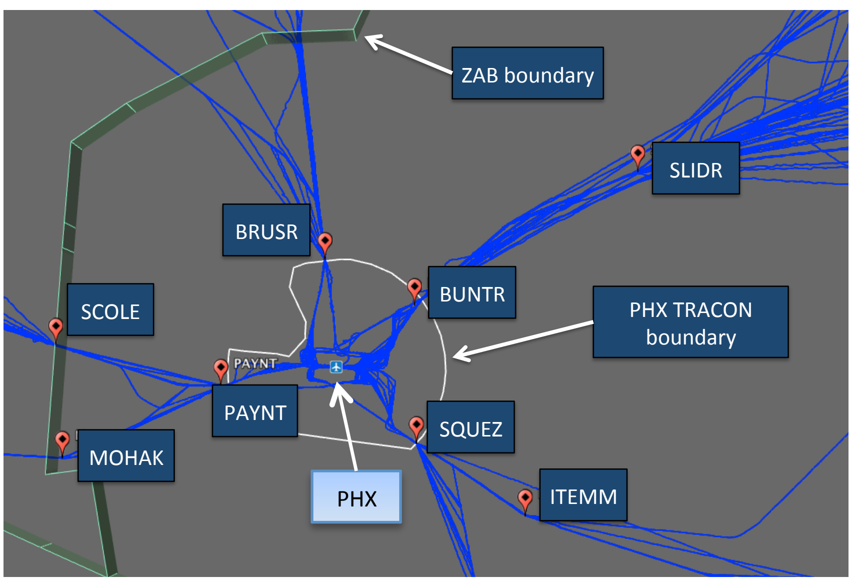

Figure 4. ZAB merge waypoints and Airline B PHX arrival flight paths for April 19th, 2012.

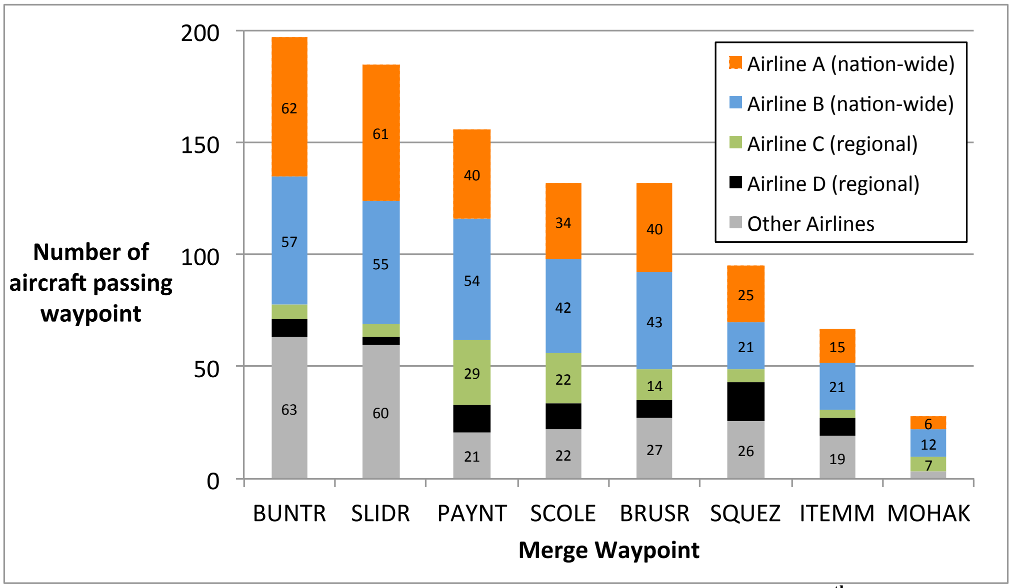

Figure 5. Air traffic through merge waypoint by airlines for April 19th, 2012.

A. PM Results: Gain and Cost

PM effectiveness in providing high-equipped airlines with operational advantages were examined under the four scheduler variants mentioned in Section IIIB, based on the assumption that all competitor flights are low-equipped. Table 3 display the percentage of flights that was re-sequenced ahead of competitor flights. For example, if an airline had 100 flights arriving to PHX and 20 of those flights were re-sequenced ahead of at least one competitor aircraft, the entry in Table 3 will be 20%. Figure 6 displays the fleet-wide airtime savings for the high-equipped airlines. Airtime savings are further broken down by aircraft type in Table 4. The choice of passing option had a notably larger impact on PM benefits compared to the speed change options. Enabling passing between any flight paths more than doubles the fleet-wide re-sequence opportunities and triples the total airtime savings across all the airlines examined. Airlines A and B experience higher total re-sequence opportunities and airtime savings compared to airline C and D. However, PM benefits for airline C exceed the others when the fleet size is also considered. For example airline C, composed of 24 aircraft making 56 flights into PHX saved approximately 4 hours of airtime and 71% of its flights passed at least one competitor aircraft under PMRS 4. On a per aircraft basis, airline C saved 10 minutes of flight time, whereas flights in airline A and B saved only 3-4 minutes. PM is only considered between aircraft operated by different airlines and higher operational market share (lower competitor presence) most likely lead to lower re-sequence probabilities and airtime savings for airline A and B.

Table 3. Percent of flights that was re-sequenced ahead of at least one competitor aircraft.

Airline	PMRS 1	PMRS 2	PMRS 3	PMRS 4
A	21%	21%	52%	52%
B	22%	22%	43%	42%
C	27%	27%	71%	71%
D	9%	9%	50%	48%

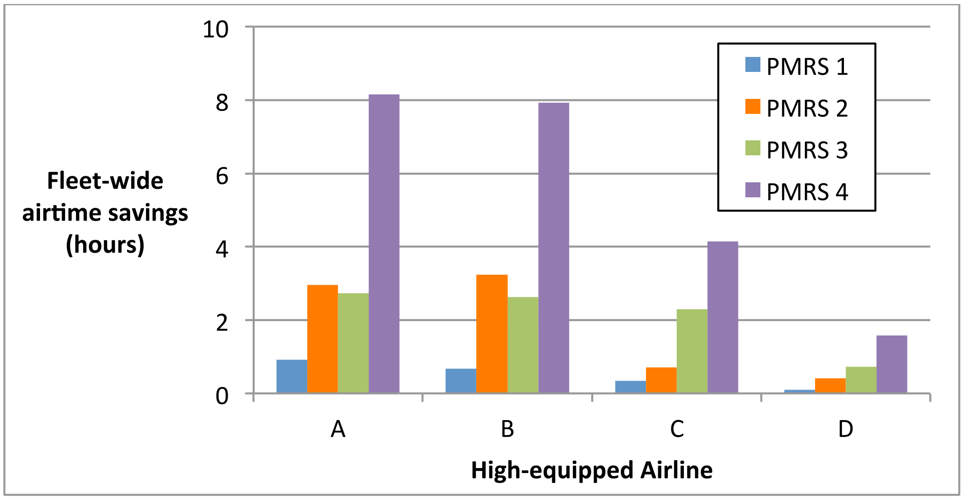

Figure 6. Fleet-wide PM airtime savings.

Table 4. Fleet-wide PM airtime savings by aircraft type (hours).

Airline	Aircraft Type	Fleet Size	Flights	PMRS 1	PMRS 2	PMRS 3	PMRS 4
A	A319	43	75	0.28	0.99	1.04	2.82
	A330	45	65	0.42	1.02	1.24	3.25
	A321	24	29	0.14	0.79	0.45	1.90
	B752	7	8	0.07	0.16	-0.01	0.19
	TOTAL	119	177	0.90	2.62	2.43	6.88
B	B733	36	43	0.07	0.53	0.58	1.45
	B735	6	7	0.07	0.12	0.06	0.25
	B737	114	130	0.54	2.59	1.98	6.22
	TOTAL	156	180	0.74	3.42	2.78	8.17
C	CRJ200	17	49	0.35	0.63	2.20	3.89
	CRJ700	6	8	0.01	0.04	0.10	0.21
	CRJ900	1	1	0.00	0.04	0.00	0.04
	TOTAL	24	58	0.28	0.61	2.05	3.48
D	CRJ200	3	7	0.00	0.18	0.24	0.52
	CRJ900	18	32	0.08	0.20	0.52	1.02
	DH8B	3	7	0.00	0.02	-0.02	0.04
	TOTAL	24	46	0.08	0.21	0.38	0.82

Table 5 organizes the change in fuel cost for each PMRS configuration compared to the baseline trajectory assuming jet fuel price fixed at $0.43/lb. The any flight path passing option coupled with the high-equipped speed up first option (PMRS 4) results in the highest airtime savings and re-sequence opportunities, but requires more fuel for the high-equipped flights compared to other PMRS variants. This outcome was expected as high-equipped speed up first option (PMRS 2 & 4) usually allows the high-equipped flights to land sooner reducing airtime, but forces the aircraft to fly outside the optimal cruise speed. Low-equipped flights receive less impact in terms of airtime or fuel cost. Conversely, the low-equipped slow down first option (PMRS 1 & 3) maintains similar airtime and fuel cost for the high-equipped compared to the baseline, but increases the financial burden on the competitor's low-equipped flights by forcing them to fly slower (increased fuel cost and airtime). Competitor obstruction, however, is not considered as an airline "return on investment" and such indirect benefits are currently not reflected in analysis.

Table 5. Change in fuel cost from PM speed change for high-equipped flights.

	PMRS 1	PMRS 2	PMRS 3	PMRS 4
A	+$328 (0.03%)	+$1,846 (0.18%)	+$1,967 (0.19%)	+$6,825 (0.67%)
B	-$206 (0.03%)	-$267 (0.04%)	-$402 (0.05%)	-$269 (0.67%)
C	+$212 (0.34%)	+$473 (0.77%)	+$844 (1.30%)	+$2,448 (3.97%)
D	+$18 (0.02%)	+$412 (0.51%)	+$810 (1.00%)	+$1,636 (2.00%)

The net balance between DOC savings from reduced airtime and change in fuel cost using PM on the 4/19/12 flights to PHX is summarized in Table 6. All airlines received positive benefits for all four PMRS configurations. Airline B received the most financial benefits from PM out of the four airlines investigated, partly due to the lower fuel cost achieved by the airline. All other airlines were required to burn more fuel under PM, offsetting the gains from DOC savings. It is still unclear why only airline B required less fuel in all PMRS configurations compared to other airlines. The minor change in fuel burn (ranging between 0.03% to 0.67%) may simply be within the error bounds of the fuel estimation procedure or flight characteristic of the B737 series, and is currently under investigation. Airline C was third in terms of the total financial benefits gained but the per aircraft PM return surpasses that of all other airlines if normalized by fleet size, as shown in Table 7.

Table 6. Fleet-wide net PM savings from change in DOC and fuel requirements.

	PMRS 1	PMRS 2	PMRS 3	PMRS 4
A	$958	$3,867	$1,945	$7,326
B	$1,388	$5,924	$4,981	$14,100
C	$310	$577	$2,544	$3,660
D	$114	$212	$304	$779

Table 7. Per aircraft PM savings from change in DOC and fuel requirements.

	PMRS 1	PMRS 2	PMRS 3	PMRS 4
A	$8	$32	$16	$62
B	$9	$38	$32	$90
C	$13	$24	$106	$153
D	$5	$9	$13	$32

B. ADS-B-IN Investment Collection Time via PM

The previous section investigated the net PM return, and now the capital cost along with the return payment period needs to be considered to complete the investment payoff analysis. In summary, PM pays-off ADS-B-In equipage cost by DOC savings from reduced airtime. ADS-B-In cost is assumed to be fixed based on the aircraft production status, but the hourly DOC is unique for each aircraft. ADS-B-In cost for each aircraft is translated to daily airtime reduction requirements based on the individual hourly DOC in Figure 7 below, for a 12, 24 and 36 month return payment period. For example, a single A319 aircraft needs to reduce its airtime by 0.42 hours daily while maintaining the same operations in order to pay off for ADS-B-In (In-Production: $270,000) over a 12 month period. Referring back to the previous section, the average airtime reduction per aircraft for airline A in PMRS 4 was approximately 0.06 hours. Thus, it will take airline A over 80 months to complete the ADS-B-In payments solely through DOC savings in the PHX/ZAB airspace. This estimation does not include the extra fuel required in maneuvers to re-sequence flights on the same path, service out time for the retrofit or interest, so the actual pay-off time is expected to be longer. Under the fleet mix and equipage assumptions in this study, it would be infeasible to fulfill such expectations with PM alone in the PHX/ZAB. Table 8 below encapsulates the percent of ADS-B-In investments that can be collected after 18 months of PM, which is 19% at best. PM should be activated in other airspace to extend its financial benefits.

Table 8. ADS-B-In investment collection rates after 18 months of PM.

Airline	PMRS 1	PMRS 2	PMRS 3	PMRS 4
A	2%	6%	3%	12%
B	1%	6%	5%	15%
C	2%	3%	13%	19%
D	1%	2%	2%	6%

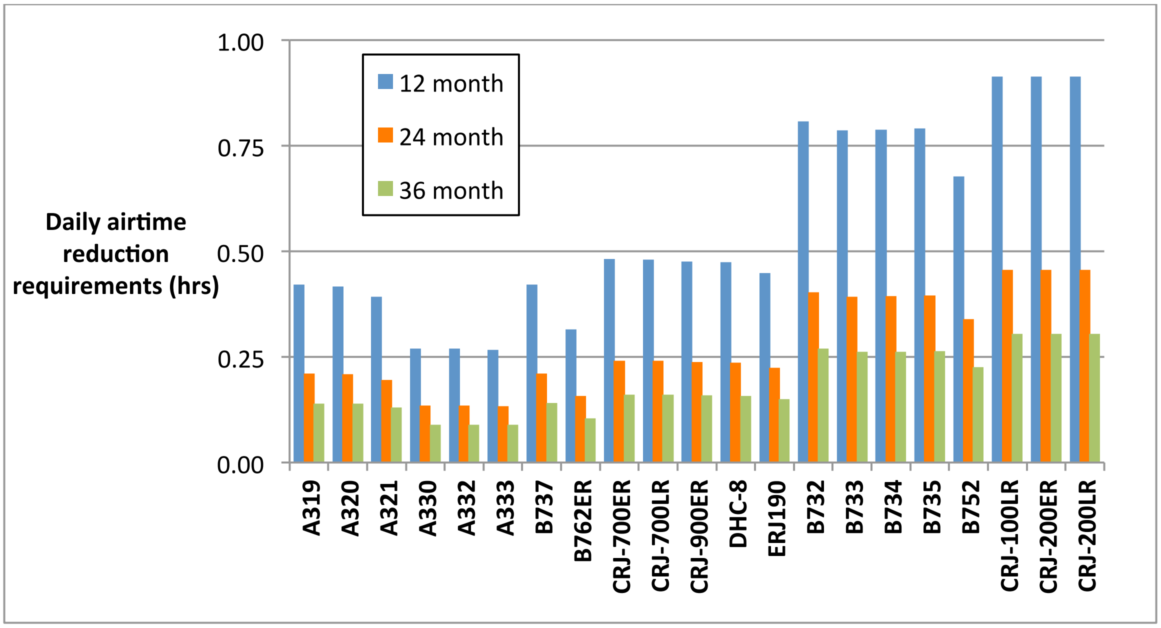

Figure 7. Fleet-wide PM airtime savings requirement.

C. PM potential at other US airspaces

This section examines the airline fleet utilization pattern across the NAS to identify candidate airports with high PM yield extension potential, after PM is implemented in PHX in an effort to increase financial benefits for airlines. Airline A was selected for this particular case study using 2010 air traffic data from the Bureau of Transportation Statistics (BTS)[23]. Four main factors were considered to recognize the PM yield extension potential in other airports. First is the fleet's operational overlap between the candidate airport and PHX. This airport search effort assumes that PM will first be enabled at PHX, and high commonality in aircraft usage between PHX and the candidate airport will permit maximum benefits with less aircraft to upgrade. Aircraft tail number tracking from the T-100 domestic segment data from the BTS was used for this analysis. Second is the combined number of arrival operations carried out by the shared aircraft at PHX and the candidate airport. Similar to the aircraft sharing principle mentioned earlier, a larger number of operations are generally preferred as they increase total re-sequence opportunities. Third is the operational market share. Operational market share is the ratio between airline A's annual arrivals and the candidate airport's total annual arrivals across all airlines. For example, if the total annual arrivals to PHX were 1,000 and airline A had 100 arrivals, airline A's operations market share would be 10%. PM is only considered between aircraft operated by different airlines, and higher competitor presence (lower market share) leads to higher re-sequence probabilities. Low market share and high operations are essentially opposing factors, and further PM studies at multiple airports will help determine which factor has a more significant impact on PM benefits. The fourth factor is the annual delay minutes experienced by the airline for arrival operations to the airport. PM will produce a higher yield in congested airspace for high-equipped airlines by transferring delays to low-equipped, competitor aircraft and also preventing other high-equipped competitor aircraft from being re-sequenced ahead in the queue.

Table 9 summarizes information on the four factors mentioned above for some of the domestic hub-airports served by airline A, with ranking factors in the column numbered by the order it was discussed in the previous paragraph. Airports in the table are listed in descending order of the total arrival operations carried out by shared aircraft between PHX and the candidate airport. At first glance, Charlotte Douglas International (CLT) and Philadelphia International (PHL) seem to be the ideal candidates to enable PM next. The aircraft sharing ratio with PHX, flight delay, and arrival operations by shared aircraft are all high. However, CLT and PHL have a relatively large market share of 35% and 23% respectively, which may hinder PM benefits. McCarron International (LAS) is an attractive airport for PM from a market share and aircraft sharing point of view, but delay minutes and arrival operations are much lower compared to CLT and PHL. Depending on the employed metric, PM implementation preference order changes slightly. To establish a more explicit airport PM implementation preference ranking, the relative importance of each factor mentioned above needs to be determined from detailed operational PM benefits study at multiple airports as well as inputs from various subject matter experts (e.g., ATC and airline personnel).

Table 9. Operations information of future PM candidate airports.

Candidate airport	①A/C shared with PHX	①Fleet size	①A/C sharing ratio	②Candidate airport + PHX arrivals by shared A/C	③Operational market share	④ Annual delay (min)
CLT	322	368	0.88	124,362	0.35	172,616
PHL	331	377	0.88	90,770	0.23	160,164
LAS	193	212	0.91	64,443	0.06	20,038
LAX	209	229	0.91	59,777	0.03	15,646
DFW	296	321	0.92	59,719	0.02	15,294
DEN	228	250	0.91	57,901	0.02	10,714
DCA	247	275	0.90	54,465	0.16	44,970
BOS	268	293	0.91	54,025	0.12	80,520
SFO	187	203	0.92	52,026	0.03	52,264
ORD	278	296	0.94	50,144	0.02	49,565

V. Conclusion and Future Work

In this paper, the return on investment for Automatic Dependent Surveillance-Broadcast-In equipage based on Preferential Merging was investigated using a queue-based arrival scheduler and simulation of one day of operations at Phoenix Sky Harbor International airport. Analysis in this initial evaluation revealed that over an 18 month period, Preferential Merging can return 19% of the Automatic Dependent Surveillance-Broadcast-In investment for the best case configuration of the scheduler logic, and 1% for the worst. Note that these benefits are a "bonus" to the conventional benefits provided by Automatic Dependent Surveillance Broadcast-In investment such as increased airspace capacity and availability of more efficient flight procedures. Also the payoff rates reported here are based on the assumption that Automatic Dependent Surveillance-Broadcast-In will be in place for the entire airline fleet arriving to Phoenix airport. Prioritizing avionics equipage on aircraft based on operations frequency will have a noticeably large impact on pay-off rates. Further, aircraft maneuvers to comply with the re-sequenced schedule are currently restricted to speed change on fixed paths from historical data. Allowing additional maneuvers such as direct-to will save additional fuel and direct operating cost for aircraft that equip with Automatic Dependent Surveillance-Broadcast-In. Lastly, this study investigated benefits for arrival flights to Phoenix Sky Harbor International airport only, and deploying the Preferential Merge Re-sequence Scheduler to other airports is expected to improve the overall investment payoff rate across most airlines. Completing a National Airspace System-wide simulation and several other airport specific analyses of Preferential Merge Re-sequencing will provide a more comprehensive projection on anticipated financial benefits.

The results reported in this paper describe only the initial estimation of Preferential Merging benefits; as such, there is more work to be done. The first step is investigate Preferential Merging benefits on air traffic across multiple days with varying operating conditions to examine its sensitivity. Second, is to integrate a trajectory trial planner with the scheduler to implement maneuvers beyond speed control, such as altitude or path change. Airline and air traffic controller feedback regarding feasibility of the four scheduler configurations explored in this paper will also be valuable. Instead of an all-or-nothing equipage scenario among the airline fleet, developing a scheme to selectively upgrade avionics on individual aircraft with high yield potential will add further value to this study. More precise information such as aircraft direct operating and airborne cost from airlines, can enhance the accuracy of the benefits estimates as well.

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